

# ELECTRA: A REPETITIVELY PULSED KrF LASER SYSTEM\*

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## Abstract

Electra is a repetitively pulsed, electron beam pumped krypton fluoride (KrF) laser at the Naval Research Laboratory. It is used to develop the technologies required for a large, durable and repetitive laser driver for Inertial Fusion Energy (IFE). This paper gives an overview of the Electra program, and then concentrates on the most recent research advances in electron beam propagation in the diode and deposition in the laser gas, repetitive laser energy extraction in an oscillator mode, the laser gas recirculator, and KrF kinetics.

## I. INTRODUCTION

Direct drive with KrF lasers is an attractive approach to fusion energy: KrF lasers have outstanding beam spatial uniformity, which reduces the seed for hydrodynamic instabilities; they have an inherent short wavelength (248 nm) that increases the rocket efficiency and raises the threshold for deleterious laser-plasma instabilities; and they have the capability for “zooming” the spot size to follow an imploding pellet and thereby increases efficiency.

The components that need to be developed are: a durable and efficient pulsed power system; a durable electron emitter; a long life, transparent pressure foil structure (hibachi); a laser gas recirculator; and long life optical windows. The technologies developed on Electra will be directly scalable to a full size fusion power plant beam line. Some of the fusion energy requirements for a KrF IFE laser are based on the Sombbrero power plant studies [1] and on high gain target designs [2,3] (see Table 1). Beam quality and optical bandwidth requirements are easier to meet, while system efficiency, durability and lifetime are the most demanding requirements.

Electra [4] is part of a larger, coordinated, focused research program to develop Laser Inertial Fusion Energy [5]. The approach is based on lasers, direct drive targets,

and dry wall chambers that are developed in concert with one another to ensure a coherent laser fusion energy system.

**Table 1.** Fusion energy requirements for a KrF IFE laser.

Parameters	IFE
Beam quality (high mode)	0.2%
Beam quality (low mode)	2%
Optical bandwidth	1-2 THz
Beam Power Balance	2%
Rep-Rate	5 Hz
Laser Energy (beam line)	40-100 kJ
Laser Energy (total)	1.7-4 MJ
Cost of pulsed power <sup>(1)</sup>	< \$10/J(e-beam)
Cost of entire laser <sup>(1)</sup>	\$225/J(laser)
System efficiency	6-7%
Durability (shots) <sup>(2)</sup>	3 x 10 <sup>8</sup>
Lifetime (shots)	10 <sup>10</sup>

(1) 2003 \$. Sombbrero (1992) gave \$4.00/J (pulsed power) and \$180/J (entire laser)

(2) Shots between major maintenance (2 years)

## II. THE ELECTRA LASER PROGRAM

Electra is a KrF laser facility with a repetition rate of 5 Hz and a laser energy of up to 700 J per pulse. The key components of the Electra main amplifier include two pulsed power systems, 27x97 cm<sup>2</sup> cathodes, pressure foil support structures (hibachi); a laser cell with a double sided e-beam pumped cross-section of 30x29 cm<sup>2</sup>; a laser gas recirculator, laser cell windows, and output optics (see Fig. 1). The e-beam is guided from the cathode through the hibachi into the laser cell by an axial magnetic field of 1.4 kG.

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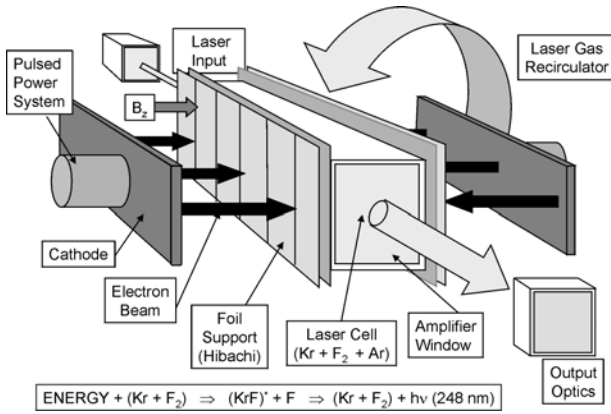
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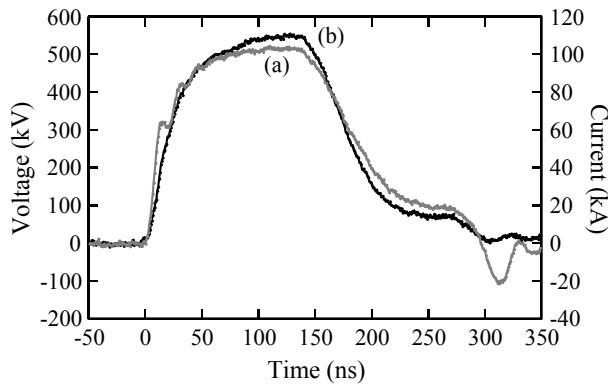
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### A. Pulsed Power Systems

Each pulsed power system consists of a capacitor bank that feeds the primary side of a step-up autotransformer. The secondary side charges a pair of coaxial, water dielectric, pulse forming lines. The energy in the lines is then switched into the vacuum diode (load) using laser-triggered spark gaps. The system operates at 400-550 kV, 70-120 kA, and with a 160 ns FWHM pulse duration. Figure 2 shows typical voltage and current waveforms of a single diode. The pulsed power system can run at 5 Hz continuously for  $10^5$  shots without refurbishment. (Refurbishment is a simple matter of replacing two pairs of electrodes.) A detailed description of the system is given in reference [6]. Although this “first generation” system does not meet the IFE requirements for durability and efficiency (see Table 1), it is an excellent test bed for developing laser components.



**Figure 1.** The main components of an electron beam pumped KrF laser.



**Figure 2.** Typical voltage and current waveforms using a velvet cathode. (a) diode voltage and (b) diode current.

An advanced pulsed power system that can meet all the IFE requirements for durability, efficiency, and cost is currently under development [7]. It is based on an ultra fast Marx with laser gated semiconductor switches, a single stage magnetic compressor, and a transit time isolator. Present design parameters are 800 kV, 170 kA, with a 60 ns risetime, 600 ns flat-top, and 60 ns fall time. System models predict a flat-top e-beam energy over wall

plug efficiency of 85%. End of life component testing on capacitors and dielectrics at full energy density have been carried out to over  $3 \times 10^8$  pulses.

A smaller pulsed power system is being built that will serve as a driver for the pre-amplifier in the Electra laser system. It uses a similar architecture as the advanced fusion energy driver, except for the ultra fast Marx that will initially employ spark gaps [8]. The driver will also be used as a test bed for the advanced laser gated semiconductor switches that will replace the spark gaps in 2006.

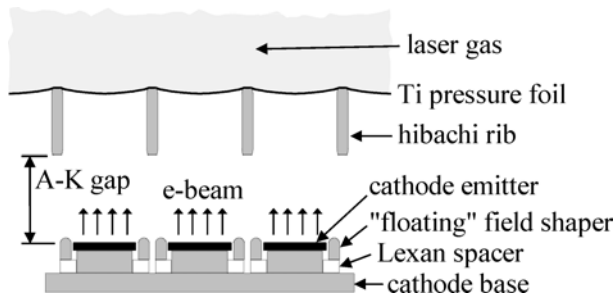
### B. Cathode

One of the key challenges for a long-lived KrF laser is the development of a durable cathode. The Electra program is evaluating a number of cathode options that can meet the requirements for risetime ( $< 40$  ns), uniformity ( $< 10\%$ ), impedance collapse ( $< 1$  cm/ $\mu$ s), and durability ( $> 3 \times 10^8$  shots). Presently, double density velvet cloth, made by Youngdo Velvet, product # AW-1100, is used as a cathode to test various laser components. To meet the IFE requirements for durability, a ceramic honeycomb capillary discharge cathode is currently investigated. More details on this cathode are found in reference [9].

### C. Electron Beam Propagation in the Diode and Deposition in the Laser Gas

Our goal is to achieve an overall laser system efficiency of 6-7% for an IFE system. We have arbitrarily set the goal for energy deposition efficiency into the laser cell (defined as the ratio of energy deposited into the laser cell over flat-top diode e-beam energy) to 80% for a 750 keV electron beam. High energy deposition efficiency was achieved with two innovations: 1) eliminating the anode foil on the diode side of the hibachi structure, and 2) patterning the electron emitter into strips so the beam “misses” the hibachi ribs. Figure 3 shows the basic configuration of the diode. The hibachi stainless steel ribs are 5 mm in width, 28 mm deep, and they are spaced 4 cm apart. They support a 25 or 50  $\mu$ m thick titanium or 25  $\mu$ m thick stainless steel pressure foil. The cathode consists of 24 strips, each 23 mm x 27 cm, at an A-K gap of 35 mm. For deposition measurements, the laser cell is filled with krypton or a krypton/argon mixture at pressures ranging from 1 to 2 atm. Advantages of a design without an anode foil (see Fig. 3) are increased hibachi durability and no anode foil e-beam absorption or additional scattering losses.

The cathode strips are “counter-rotated” by  $6^\circ$ , and strip-to-strip spacing is increased by 0.5 mm compared to the hibachi rib-to-rib spacing to compensate for beam rotation and pinching inside the diode, respectively. To eliminate the e-beam halos of each strip cathode, “floating” electric field shapers [10] surround the cathode strips.



**Figure 3.** Diode configuration: 28 mm deep hibachi and 23 mm wide strip cathode with “floating” field shapers. The A-K gap is measured from the cathode emitter surface to the hibachi front surface.

The deposited energy has been obtained from a Baratron that measures the pressure rise in the laser cell. The measurements indicate that up to 75% of the e-beam energy is deposited inside the laser cell during the flat-top portion of the pulse. 3-D LSP [11] simulations, which include the actual diode geometry, external magnetic field, hibachi ribs, and backscattering, showed that the energy deposition efficiency is 74% for a 500 keV beam and a 25  $\mu\text{m}$  thick Ti pressure foil. This agrees well with the experimental observation.

To achieve even higher deposition efficiencies, a new hibachi with shallower ribs (13 mm instead of 28 mm) is currently under investigation. This hibachi configuration allows for a more uniform electric field at the anode, and should minimize e-beam spreading losses. Preliminary simulations showed that the ultimate goal of 80% hibachi efficiency is achievable in a full-scale (750 keV) system.

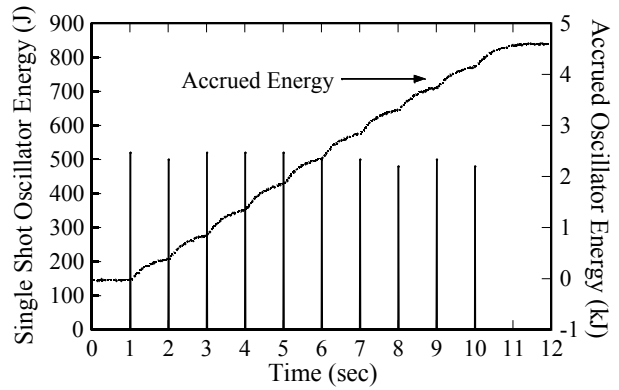
#### D. Oscillator Mode Operation

The main amplifier of Electra was operated as an oscillator by using a rectangular flat mirror (32x36  $\text{cm}^2$ ) with a 98.5% reflectance coating at 248 nm and a parallel, uncoated fused silica output coupler (33x35  $\text{cm}^2$ ) that provides a reflection of 8% (total of both surfaces). Two single sided 248 nm AR coated windows, tilted at 14 degrees, enclose the laser cell with their uncoated surfaces exposed to the laser gas. Laser light is extracted from a 30x29  $\text{cm}^2$  aperture of the laser cell. The entire laser cell dimensions are 30x128x215  $\text{cm}^3$ , whereas the e-beam pumped region is about 30x97x27  $\text{cm}^3$ .

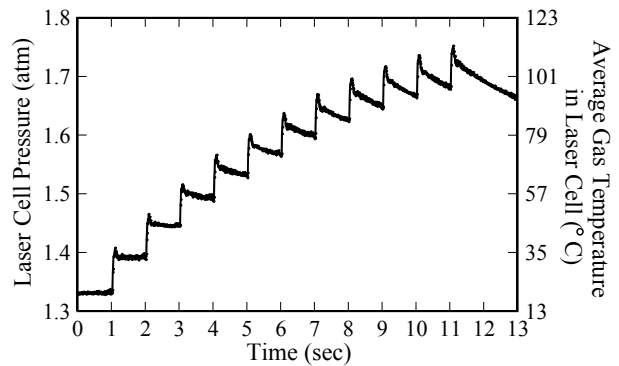
At a laser gas composition of 39.75% Kr, 60% Ar and 0.25% fluorine at a total pressure of 1.36 atm, the oscillator produced an average output energy of 500 J per shot for a 10 shot burst (see Fig. 4). The laser energy was measured with a 33x33  $\text{cm}^2$  calorimeter that has a thermal decay time of 35 seconds. When the calorimeter signal is compensated for its exponential decay, the accrued energy is 5 kJ for the 10 shot burst.

The experiment was limited to short bursts (less than 20 shots) at 1 Hz since the pressure increased rapidly inside the enclosed laser cell (see Fig. 5). Note that the oscillator energy does not show a strong dependence on the laser gas temperature (compare Fig. 4 with Fig. 5). To allow for longer bursts and higher repetition operation, a laser gas

recirculator is currently installed on Electra’s main amplifier.



**Figure 4.** Laser energy measured during a 10 shot burst @ 1 Hz. The total energy was measured with a 33 cm x 33 cm calorimeter; the signal has not been compensated for its exponential decay. The average laser energy is 500 J per shot.

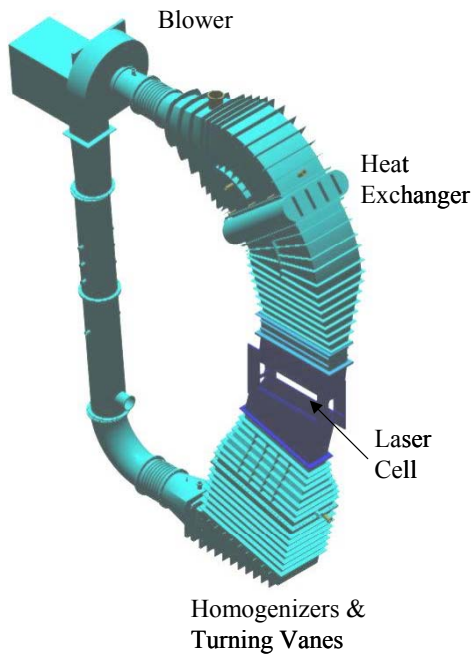


**Figure 5.** Gas pressure and temperature in the 828 liter laser cell during an 11 shot burst @ 1 Hz, using a 1 mil thick stainless steel pressure foil. The laser cell was e-beam pumped from both sides, and the diode configuration was similar to the one shown in Fig. 3.

#### E. Laser Gas Recirculator

The laser gas must be cool and quiescent on each shot to ensure a very uniform amplified laser beam, thus, a laser gas recirculator (see Fig. 6) is currently installed on Electra’s main amplifier. Initial temperature measurements of the pressure foil have been performed with a partially installed recirculator containing a volume of approximately 6000 liters. At a repetition rate of 1 Hz the foil temperature stabilizes around 360°C (see Fig. 7a), whereas at 5 Hz the foil temperature increases rapidly (see Fig. 7b). For both cases, argon at 1 atm was used inside the laser cell/recirculator. These results indicate that thermal conduction to the hibachi ribs is inadequate for the pressure foil cooling at the desired 5 Hz repetition rate. Therefore, the recirculator design includes louvers in the laser cell that can be rotated to temporarily trip the normally quiescent gas flow to turbulence, and direct the

gas flow to the pressure foils (see Fig. 8). After the e-beam energy has been deposited in the laser gas and laser energy has been extracted, the louvers are closed within 25 milliseconds. The louvers stay closed for 75 msec, which allows highly turbulent laser gas with velocities of up to 25 m/sec to stream along both pressure foils (see Fig. 8b). The louvers are then opened again with 25 msec and stay open for another 75 msec, which allows for the laser gas to return to a quiescent state again before the next shot (allowing a laser repetition rate of 5 Hz). The Computational fluid dynamic CFD analysis indicate that this technique should keep the pressure foil to below 650°F (340°C) during repetitive operation at 5 Hz. The analysis also showed that, when the louvers in an open position, there is sufficiently quiescent flow in the e-beam pumped volume of the laser cell as it is indicated by the uniform fill color in Fig. 8a. Experimental validation of this pressure foil cooling mechanism is planned in the near future.

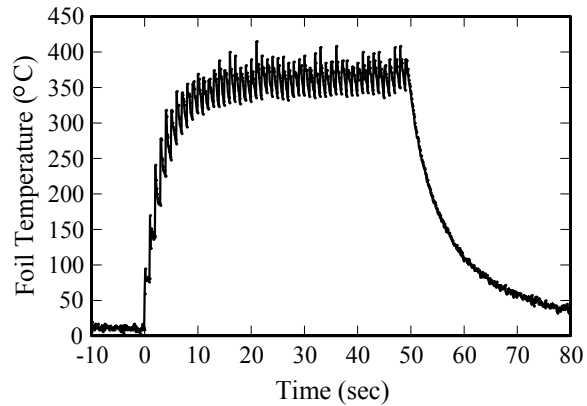


**Figure 6.** Schematic of the laser gas recirculator. It is 7.5 m high and 5 m wide.

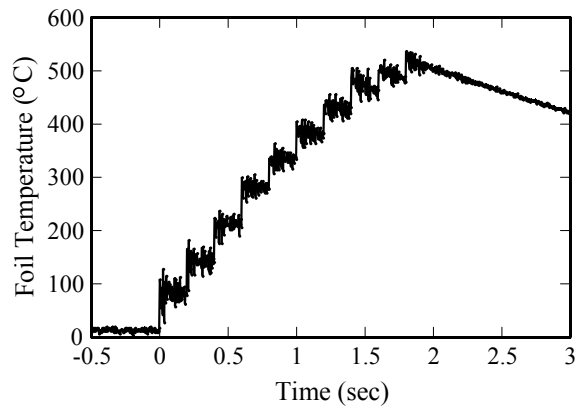
#### F. KrF Kinetics

An essential component of the Electra program for understanding the experimental results is a numerical simulation capability for the KrF kinetics. Toward this end the Orestes code has been developed to model the generation of laser light within the Electra laser cell. The code will provide understanding and reliable predictions of the laser output as a function of the electron beam properties, investigate the dynamics for pulse shaping, and develop scaling relations for a fusion energy driver. Orestes is a first principles physics code that couples various processes in a self-consistent manner. The ionization and excitation resulting from the deposition of

the electron beam in the target gas is calculated from the non-Maxwellian electron energy distribution function as determined from a Boltzmann code [12,13]. The subsequent plasma chemistry initiated by the energetic electrons is followed for 23 species subject to 119 reactions. To check energy conservation, equations for the mean electron and gas temperatures as well as the enthalpy balance among species are also followed. As noted by Kannari, *et al.* [14], it is important to model the vibrational relaxation of the KrF molecule since lasing occurs only from the lower vibrational levels of the B electronic state. Orestes employs a model based on the experimental study of the relaxation process found in reference [15].



(a)

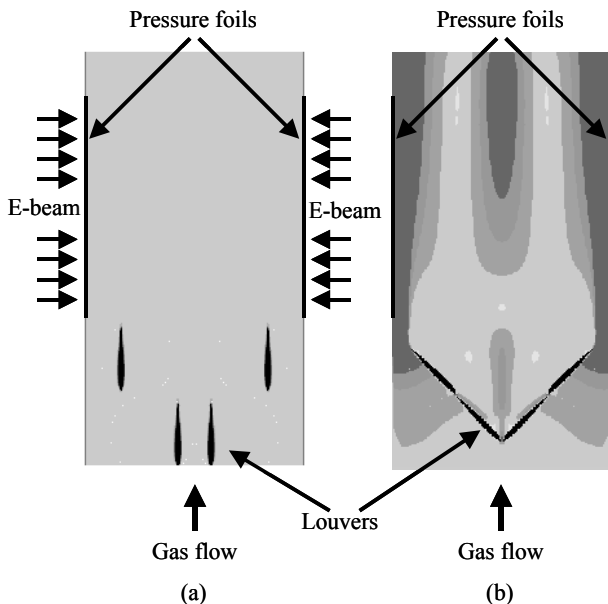


(b)

**Figure 7.** Temperature measurements of a 1 mil thick stainless steel pressure foil for (a) 50 shot burst @ 1 Hz and (b) 10 shot burst @ 5 Hz. The laser cell contained argon at 1 atm. (without gas flow).

In Orestes the time dependence of the power deposition into the target gas by the energetic electrons is taken to have the same profile as the measured power in the diode (see Fig. 2). This temporal profile can be scaled in amplitude such that the total energy deposition matches data from the pressure jump method. The power deposition is assumed to be spatially uniform at any given

time during the pulse, but the plasma evolution of the pumped plasma is followed with 1-D spatial resolution along the lasing axis. This approach accounts for the spatially dependent depletion of the KrF species resulting from saturation of the laser intensity toward the front of an amplifier. The amplification by stimulated emission of the input laser is accurately followed in a single or double pass design using the method of characteristics. A similar technique is used for an oscillator except that a small fraction of the spontaneous emission is taken to be emitted along the preferred lasing axis. Amplification of spontaneous emission (ASE) along other directions leads to incoherent propagation and detracts from the lasing efficiency. This detraction can be particularly important in moderate aspect ratio cells (say length:height = 3:1) such as envisioned for fusion energy drivers. The time-dependent ASE in the cell is followed in 3-D using hundreds of discrete ordinates to account for wall reflections and angular anisotropy [16]. Validation of Orestes is based on comparison of the calculated gain, saturation intensity, and laser output with existing experimental data from Nike [17,18], a facility at Keio University [19], and GARPUN at the Lebedev Physical Institute [20]. The data covers a broad range of conditions in beam power deposition, target gas composition, and input laser intensity.



**Figure 8.** Cooling mechanism of the pressure foil using the laser gas: (a) at  $t = 0$ , the louvers are open and the laser gas flow is quiescent at a uniform velocity of 6.8 m/sec. (b) at  $t = 100$  msec, the louvers have been fully closed for 75 msec and highly turbulent laser gas with velocities of up to 25 m/sec streams along the pressure foil to cool them.

During the past year Electra was configured as an oscillator (see Section D) and Orestes simulations were run to predict the laser yield as a function of pressure and composition. The peak electron beam power deposition

was set at  $800 \text{ kW/cm}^3$ , giving a total energy deposition of 9.8 kJ. For a fixed energy deposition Orestes predicts the laser yield to fall off at high pressures, regardless of the composition, due to three-body relaxation reactions such as  $\text{KrF}^* + \text{Kr} + (\text{Ar}, \text{Kr}) \rightarrow \text{Kr}_2\text{F} + (\text{Ar}, \text{Kr})$  and  $\text{KrF} + \text{Ar} + (\text{Ar}, \text{Kr}) \rightarrow \text{ArKrF} + (\text{Ar}, \text{Kr})$ . As the pressure is lowered at a fixed composition, a peak in the laser yield was found at  $\sim 1$  atmosphere. This peak was larger at 60% Ar (850 J) than at 40% Ar (800 J), which was larger than at 0% Ar (700 J). The  $\text{F}_2$  abundance was kept below 1%, and the remainder was Kr. The trend in these predictions were confirmed by experimental measurements, except that the falloff in yield with pressure below the measured peak was faster than calculated. This is thought to be due to the inherent reduction in the beam stopping power at low pressures. The absolute yields from Orestes were larger than those observed and this may be due to a lower power deposition in the experiments at  $\sim 1$  atmosphere than assumed for Orestes, and/or to a lower window transmittance  $T_w$ . The above quoted yields are based on a 90% one-way transmission, but subsequent calculations indicate a significant decrease in yield with lower window transmittance. Another difference between the simulation predictions and the data was the peak laser yield as a function of  $\text{F}_2$  abundance. The peak yield was measured at 0.25%  $\text{F}_2$  while Orestes had predicted the peak should be at 0.5%  $\text{F}_2$ . This is important since some designs for a fusion power driver call for a segmented amplifier with unpumped regions between neighboring diodes [21]. Since the  $\text{F}_2$  molecule is a strong absorber at 248 nm, one seeks to operate at the lowest  $\text{F}_2$  concentration possible while maintaining high total gain to limit the background absorption in the unpumped regions. The disagreement between model and experiment indicates that the kinetic reaction set, although large, needs to be expanded to include a recycling mechanism for the fluorine atom.

### III. SUMMARY

We have obtained significant advances in the development of a durable and efficient repetitively pulsed, electron beam pumped KrF laser for IFE application. These include: (i) high electron beam energy deposition efficiency into the laser gas by eliminating the anode foil and by patterning the electron emitter into strips; (ii) as an oscillator Electra reached an average laser energy of 500 J per shot during a 10 shot burst at 1 Hz; and (iii) simulations with the Orestes KrF kinetics code exhibit qualitative agreement with the trends in the experimental data.

### IV. ACKNOWLEDGEMENTS

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